Film dosimetry: Past and future

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Summary

Accurate dosimetry is a prerequisite for safe and effective radiotherapy treatments; without accurate treatments tumour control cannot be achieved, and severe complications to patients might occur, some of which can even be lethal. Worldwide, every radiotherapy institute bases its dosimetry on the ionisation chamber as the gold standard dose detector, whose calibration is traceable to a national standards laboratory.

In both routine clinical practice and research and development use of the ionisation chamber is limited by a lack of flexibility for certain geometries. Drawbacks are its size, limited spatial resolution and an inability to manipulate the ion chamber in phantoms. As a consequence, despite it having gold-standard performance characteristics, the ionisation chamber is only used in relatively simple irradiation geometries like a water phantom or homogeneous plastic phantoms.

As one of the alternatives with which to overcome these limitations film dosimetry was introduced about 25 years ago. The big advantages of film are the 2D integrated dose information, the high spatial resolution, the ability to cut it into particular shapes and the flexibility to insert film in almost all (inhomogeneous) water and water-equivalent, i.e. plastic, phantoms.

Of course, using film in daily practice has its challenges. In radiotherapy, it has been suggested that the overall dose accuracy required is at maximum 3.5% 1 SD based on a dose effect curve with a γ-value of 2. Overall dose accuracy means the accuracy over the entire dosimetry chain, i.e. from calibrating the ionisation chamber at the national standard laboratory up to the total dose delivered to the patient. To detect such overall dose accuracy, dose detectors are needed with a measurement uncertainty at least 2-3 times less than this. For film dosimetry that is a challenge.

The basic concept of film dosimetry is the determination of the amount of light transmission through each film pixel after irradiation. The output per film pixel is expressed as optical density and has to be converted to a dose value. Twenty-five years ago, film dosimetry was a relatively unknown tool. Since then, it has been better characterized and it remains unsurpassed in its spatial resolution and flexibility. As water is the preferred medium for measurements and the ionization chamber is the “gold-standard dose detector”, film

characteristics were also determined in water and (if possible) benchmarked against ionisation chamber data.

Radiographic Film dosimetry in Radiotherapy

25 years ago radiographic film was the only option available for diagnostic and radiotherapy applications. It is based on the radiation induced transition of the silver bromide AgBr molecule into metallic silver (Ag). To fixate the latent image, a chemical development and fixation process is required. At that time, commercial "developer" and "fixation" systems were in use in diagnostic radiology departments.

In this thesis, radiographic film was investigated using the CGR Sagittaire scanning electron beam system. In chapter II, the stability of the machine output was investigated and input beam parameters for treatment planning were measured. The first practical hurdle was lining up the radiographic film in a water phantom parallel to the beam axis. Application of radiographic film in water required sealing of the film in a light excluding envelope in a dark room, which could lead to small air cavities between the film and sealant. In addition, sealing made it problematic to exactly level the film edge at the water surface. The consequence was an uncertainty in film position, influencing the accuracy of the electron beam input parameters. The air cavities disturbed the dose distribution such that the film results of the first 5 mm had to be omitted. After commissioning of the electron beam planning system its output had to be tested. One of the parameters was the relationship between electron beam spread with depth and field size which were dependent on the construction of the electron beam applicator. The electron beam dose calculation model had to be improved in order to interpret the treatment planning output data in challenging planning situations (chapter IV).

The next piece of work focused on the scanning photon and electron beams of the Scanditronix MM50 racetrack microtron. This highlighted the difficulties of using radiographic film as accurate dose detector systems. From a theoretical point of view the non-water equivalence of film was known and some experimental solutions to deal with that had been published. Experiments were performed to detect the magnitude of the energy dependence of film as a function of field size and phantom depth (chapter III). Later on, film dosimetry was used to determine dose in adjacent electron and photon fields.

This work also identified the instability of the film developing and fixation process. For diagnostic applications these instabilities were not relevant. However, for radiotherapy small variation in those parameters influenced the number of Ag atoms converted in the film, introducing a variation in optical density not related to any dose variation. A well-defined working process helped to control this variance in one measurement session but didn't guarantee similar results over multiple sessions. This necessitated extensive film calibration measurements at each session to maintain optimal dose accuracy. In chapter VI a practical method was developed to limit the extra work that this generated.

Radiochromic Film dosimetry in Radiotherapy

Ten years ago radiographic film ceased to be used. With the development of digital 2D measurement technology for diagnostic applications, the developing and fixation machines disappeared. Alternative digital detector systems, like 2D ionization chamber and 2D diode arrays, plastic scintillation detectors and 3D gel dosimetry were developed. However, none of them matches the potential of film in terms of spatial resolution and phantom flexibility.

At that time, a new generation of film, called radiochromic film, of the Extended Beam Therapy (EBT) type, was introduced as a successor for radiographic film. Radiochromic film is based on polyesters and on radiation induced transition of monomers to polymers. Big advantages of this type of film over radiographic film are its self-developing property, its near water-equivalent material and a lack of energy dependence, its suitability in daylight and its water resistance. Digitizing the film image by cheap standard commercial flatbed scanners also looked promising. Therefore, in chapter VII the overall accuracy in absolute dose was investigated for the first EBT film type. The results indicated substantial improvements compared to the experience with radiographic film.

Unfortunately, the manufacturing facility for EBT disappeared and alternative facilities could not provide comparable consistency in the amount of monomers per crystal as well as a constant film thickness. This limitation was tackled by adding a dye to the crystals in a constant ratio to the monomers: EBT-2 film. With the flatbed scanner, the visible light transmission through each film pixel can be read out in red, green and blue signals. The red and green signals are directly related to the amount of polymers induced. The dye, mainly visible in the blue color channel, is almost insensitive for dose so the signal variation in blue

can be a surrogate measure for the thickness of the film. Assuming the dye is mixed well with the monomers during the manufacturing process the blue channel signal can therefore be used to correct for variation in film thickness and the amount of monomer concentration per crystal. In daily practice this method is called “the triple color correction method”.

A problem with commercial flatbed document scanners is amplification of the optical density for film pixels situated towards the sides of the scanner glass bed, i.e. over the width of the scanner. In film dosimetry, this is called the lateral scan effect. The origins of this effect are dealt with in chapter VIII. The primary problem is the design of flatbed scanners requiring a redesign to solve it. In the meantime, in-house correction software has been developed to correct for the lateral scan effect. So far, this has not been adequately addressed by commercial software packages. Ongoing research deals with another intriguing observation: the small difference in photon beam dose decay with depth in a water phantom, i.e. percentage depth dose, that is present between ionization chamber measurements and film. To understand the origin of this small difference, several percentage depth dose curve measurements were performed in electron beams of different energies. For electron beam dose distributions, a perfect agreement between ionization and diode measurements was observed from d_{max} to a depth beyond the electron range. In contrast, a systematic deviation for all energies was observed in the buildup region, which could be explained by the difference in electron scattering between film and water (chapter IX).

Conclusions, state of the art and challenges.

The experience with electron beam percentage depth dose curve measurements using radiochromic film reminds us that the dosimetric term “water equivalence” has to be considered carefully. Nevertheless, for routine clinical applications radiochromic film seems to be a powerful 2D dose detector which can be used to verify dose calculations for both standard and advanced irradiation techniques like VMAT. Current absolute dose accuracy is better than 2.0 % 1 SD, which can probably be improved.

Despite this success, there is still a hesitation in many institutes to implement radiochromic film dosimetry. The primary reason is clear: implementation requires manpower and time to build up experience and knowledge. Additional hurdles include the fact that radiochromic

film is still being improved, and the lack of a commercial readout software package that addresses all the technical challenges.

Recent improvements in the film, as a result of changing the aspect ratio of the crystals, led to the next EBT generation; Extended dose film type (EBT-XD), introduced in 2015 with a dose range up to 40 Gy.

Ongoing research on radiochromic film has helped to secure its future. New scenarios like implementing MRI-guided radiotherapy and proton therapy are expected to further prove the value of film dosimetry, as well as to present new challenges. For MRI, there is the question of whether polymer creation is dependent on the magnetic field. For proton therapy, there is the mismatch between Bragg peak curves determined with ionization chamber and film, which may be due to the physics of interaction and polymerization reactions.

Overall, this thesis shows that, radiochromic film has fulfilled its promise of 25 years ago, to become a powerful present day dosimetry tool. Although technical challenges remain, in contrast to radiographic film, they seem solvable. Therefore, in conclusion: let’s implement radiochromic film dosimetry worldwide as the preferred 2D dose detector system!